SHORT-CAVITY SQUEEZING IN BARIUM

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Abstract

Broadband phase sensitive noise and squeezing have been observed experimentally in a system of barium atoms interacting with a single mode of a short optical cavity. Squeezing of $13\pm3\%$ was observed. A maximum possible squeezing of $45\pm8\%$ could be inferred for our experimental conditions, after correction for measured loss factors. Noise reductions below the quantum limit were found over a range of detection frequencies 60-170 MHz and were best for high cavity transmission and large optical depths. The amount of squeezing observed is consistent with theoretical predictions from a full quantum-statistical model of the system.

Introduction

The model of the interaction between a cavity mode and an ensemble of two level atoms is of fundamental importance in quantum optics (Ref. 1). Theory (Refs. 2-4) and experiment (Refs. 5-6) indicate that a particularly favorable configuration for squeezing in this model exists where decay rates of the atomic polarization and the cavity mode are approximately matched. To achieve the matching of rates without degrading the cavity finesse the cavity length must generally be reduced to a few millimetres; hence the term 'short-cavity squeezing'. Orozco et al. observed 30% squeezing in atomic sodium in this regime (Refs. 5-6). The $J=0 \rightarrow 1$ 553 nm transition of ^{138}Ba is a suitable medium to test detailed theoretical predictions of the dynamics of the cavity-atom interaction. Its simple structure allows us to avoid the complications of optical pre-pumping, necessary to restrict alkali atoms to two-level behaviour.

Experiment

A schematic diagram of the experimental arrangement is shown in Figure 1. A cw ring dye laser supplies 300 mW of light at 553 nm. The laser is frequency stabilized to 1 MHz. The first -
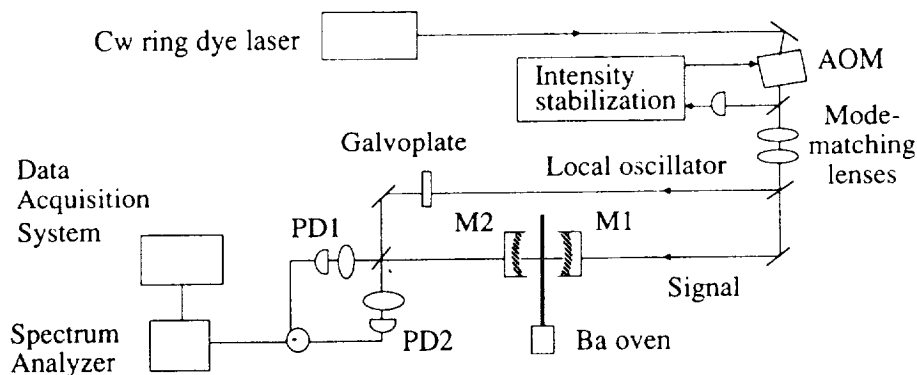

Figure 1. Experimental arrangement

order diffracted beam from an acousto-optic modulator (AOM) passes through a pair of mode-matching lenses and is divided into local osillator and signal beams with a 50% beamsplitter. The AOM serves to isolate the laser from cavity feedback, and is also operated as an intensity stabilizer. The phase of the local oscillator (LO) with respect to the signal beam phase may be varied with a scanning galvoplate, and the LO and cavity output beams are combined on a 50% beamsplitter. The output ports of the beamplitter are focused on to photodiodes PD1 and PD2 in the balanced homodyne detection system. Typically the detector gives 2 dB of quantum noise above amplifier noise at 130 MHz for 1 mA of current. The noise spectrum is displayed on a spectrum analyzer and recorded on a computer.

The optical cavity is comprised of two dielectric mirrors mounted on piezoelectric stacks separated by 4.3 mm. It is held in a stainless steel chamber evacuated to 10^{-6} torr. The input coupler M1 has transmission coefficient T1 < 0.001 and a radius of curvature Rz1 of 1 meter. The output coupler M2 has T2 = 0.036 and Rz2 = 2 m. The cavity finesse is measured as F=150 ±10 and the throughput on resonance as 1.3%. The cavity beam waist is calculated to be 92 μm.

A high-density collimated beam of barium is generated and injected perpendicularly to the cavity mode. Optical depths of up to $\alpha_0 l$ =3.5 can be achieved for a beam of diameter 2.3 mm. The FWHM of the absorption peak is 44 MHz for $\alpha_0 l$=3.5, where these values are measured using a monitor beam perpendicular to both cavity axis and atomic beam. The natural linewidth of the atomic line is γ=20MHz. The additional width can be attributed to residual Doppler broadening. We have $\gamma_\perp/\kappa$=0.08 for this experimental configuration, where $\gamma_\perp$=2γ is the transverse atomic decay rate for purely radiative decay, and κ is the decay rate of the cavity mode.

Results

Figure 2 shows a spectrum analyzer trace with 13±3 % squeezing, after corrections are made for the electronic noise contribution. It was observed for a cavity input intensity of 14 mW, atomic beam optical depth $\alpha_0 l$ = 2.7 and an atomic detuning of 600 MHz below the 553 nm transition. The
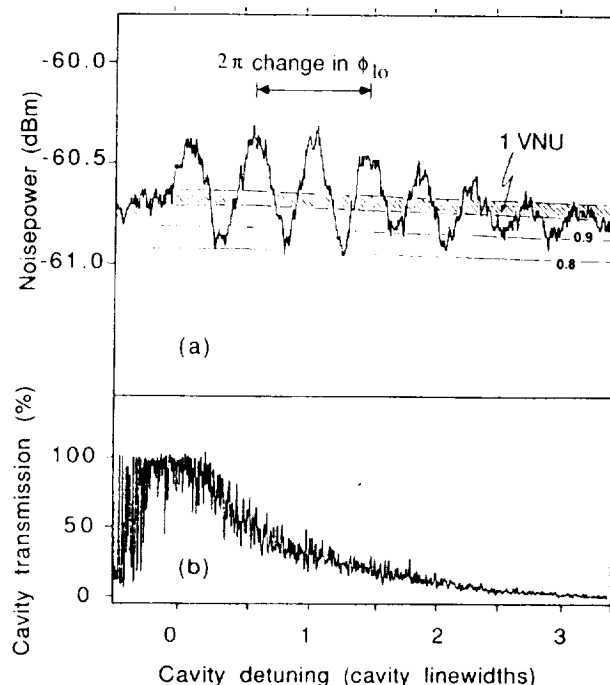

Figure 2. Noise power (a) and cavity transmission (b) recorded for optical depth $\alpha_0 l$=2.7, atomic detuning 600 MHz below the transition, cavity input power 14 mW, detection frequency 147 MHz.

detection frequency was 147 MHz. A 4-second quantum noise recording was taken while scanning the phase of the local oscillator and simultaneously sweeping through the cavity resonance. The modulated signal in Fig. 2a is the noise power. The quantum noise limit (equivalent to 1 Vacuum Noise Unit, or 1 VNU) is given by the center of the solid bar. It is obtained by recording a noise trace with cavity output blocked, under the same experimental conditions. The width of the bar represents the rms fluctuations of the noise trace. The quantum noise limit trace has been corrected for the non-negligible amount of power in the cavity output (0.18 mW compared to 1.1 mW in the LO beam). Figure 2b shows cavity transmission plotted in units of cavity linewidths from the resonance peak.

We see large amounts of phase sensitive noise near the peak of cavity transmission, together with clear reductions below the quantum noise limit, with both noise and squeezing decreasing with the sweep though the cavity. Other data reveal that squeezing exists for a broad range of frequencies 60-170 MHz, and for a bistable cavity. In the bistable regime phase sensitive noise and squeezing are seen predominantly on the upper branch.

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Figure 3 simulates the experiment, using a plane wave ring-cavity quantum theory of squeezing in optical bistability (Refs. 3-4). The cooperativity, cavity characteristics and atomic detuning are those of the results in Figure 2, within experimental uncertainties; cooperativity $C=\alpha_0 lF/(2\pi) = 64$, atomic detuning $\Delta=(\omega_a-\omega_L)/\gamma_\perp=50$ and $\gamma_\perp/\kappa=0.08$, where ω_a and ω_L are the frequencies of the atomic transition and the signal laser respectively. Other parameters are optimized for best squeezing. Cavity detuning is measured from the peak transmission in units of cavity linewidth and is incremented through the cavity resonance. The parameter corresponding to LO phase is varied at approximately the rate used in the experiment. Trace (a) is the squeezing spectrum plotted on a logarithmic scale against the left vertical axis, where a variance V of unity corresponds to the quantum noise limit and zero corresponds to perfect squeezing. Trace (b) is the intracavity photon number (proportional to cavity transmission), plotted on the right vertical axis and given in units of the saturation intensity on resonance (Ref. 3).

Figure 3 shows good qualitative agreement with experiment. Maximum squeezing is located near the peak of cavity resonance, and the squeezing decreases for decreasing transmission. The best squeezing at these parameters is 55%. Loss factors that reduce the amount of observed squeezing have been measured individually, as follows;
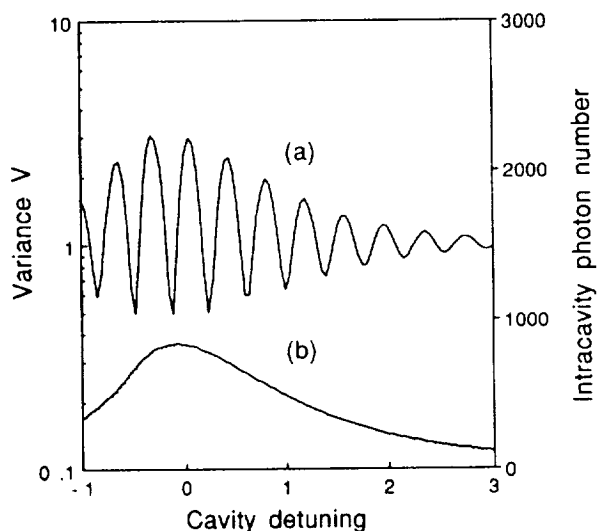

Figure 3: Theoretical modelling of experiment

cavity escape efficiency $\rho = 0.88$, detector quantum efficiency $\alpha=0.65$, mode matching efficiency $\eta^2=0.56$, propagation efficiency $T_0=0.86$, where these quantities are defined as in Refs. 6-7. We calculate that for ideal propagation and detection efficiencies the observed squeezing would equal $45\pm8\%$. This is in reasonable agreement with the theoretical prediction of 55%.

Conclusion

It was found that the interaction of a barium beam with a single mode of a short optical cavity generated reductions below the quantum noise limit of $13\pm3\%$. We infer that in the absence of loss factors $45\pm8\%$ squeezing would have been observable. This is consistent with the amount of squeezing (about 55%) predicted from a quantum theory of optical bistability.

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